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The impact of Rapido trawling for scallops, *Pecten jacobaeus* (L.), on the benthos of the Gulf of Venice

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Rapido trawls are used to catch sole around the coast of Italy and to catch scallops in the northern Adriatic Sea but little is known about the environmental impact of this gear. Benthic surveys of a commercial scallop ground using a towed underwater television (UWTV) sledge revealed an expansive area of level, sandy sediment at 25 m characterized by high population densities of scallops (2·82 m^{-2} *Aequipecten opercularis* but fewer *Pecten jacobaeus*) together with ophiuroids, sponges, and the bivalve *Atrina fragilis*. Rapido trawls were filmed in action for the first time, providing information on the selectivity and efficiency of the gear together with its impact on the substratum and on the benthos. The trawls worked efficiently on smooth sand with ca. 44% catch rate for *Pecten jacobaeus*, of which 90% were >7 cm in shell height. Most organisms in the path of the trawl passed under or through the net; on average by-catch species only formed 19% of total catch by weight. Of the 78 taxa caught, lethal mechanical damage varied from <10% in resilient taxa such as hermit crabs to >50% in soft-bodied organisms such as tunicates. A marked plot surveyed using towed UWTV before, then 1 and 15 h after fishing by Rapido trawl showed clear tracks of disturbed sediment along the trawl path where infaunal burrow openings had been erased. Abundant, motile organisms such as *Aequipecten* showed no change in abundance along these tracks although scavengers such as *Inachus* aggregated to feed on damaged organisms. There were significant decreases in the abundance of slow-moving/sessile benthos such as *Pecten*, *Holothuria*, and *Atrina*. Juvenile pectinids were abundant on the shells of *Atrina*. The introduction of a scheme of areas closed to trawling would protect highly susceptible organisms such as *Atrina* and enhance the chances of scallop recruitment to adjacent areas of commercial exploitation.

Key words: fishing, trawling impact, scallops, *Pecten jacobaeus*, *Atrina fragilis*, Adriatic Sea, Mediterranean Sea.

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Introduction

Fisheries research has traditionally focused upon gear efficiency and stock management in terms of securing sustainable yields of commercial target species, with little consideration being given to the effects of fishing on non-target species and ecosystem structure. The past decade, however, has witnessed an increasing awareness world-wide of the wider detrimental ecological effects of commercial fishing (Gislason, 1994; Jennings and Kaiser, 1998; Auster and Langton, unpubl.).

One towed gear about which little is known in terms of its environmental impact is the Rapido trawl. Bini (1960) described early designs of Rapido trawl that were towed at 3–4 km h^{-1} to catch sole (*Solea vulgaris*) and use of this gear has spread rapidly throughout the Adriatic (Piccinetti, 1967). In the late 1960s a Rapido fishery for scallops (*Pecten jacobaeus* and *Aequipecten opercularis*) opened on sandy grounds in the Gulf of Venice. This scallop fishery is now usually based on one or two consecutive year-classes of *P. jacobaeus*, around the minimum commercial size (10 cm). Scallop

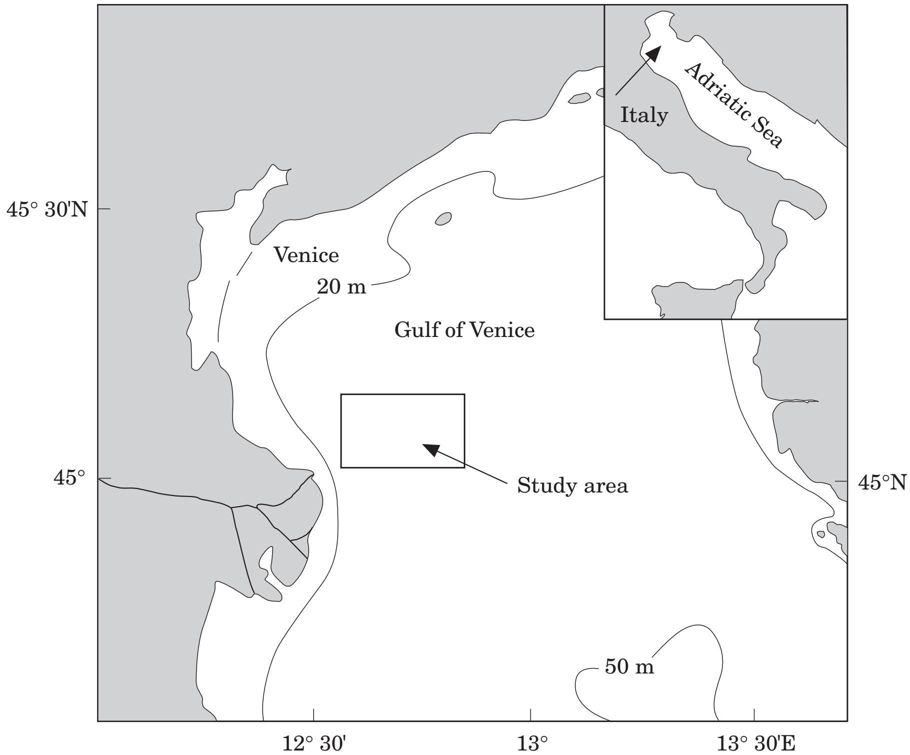

Figure 1. Location of the scallop ground studied, Gulf of Venice.

populations and landings there have shown large fluctuations over the past 30 years, determined both by the intensity of fishing effort and by mass mortalities due to hypoxic conditions that have occurred episodically over wide areas of the northern Adriatic (Froglia, 1983; Ott, 1992; Orel *et al.*, 1993; Mattei and Pellizzato, 1996). The numbers of vessels now using Rapido gear to catch scallops in the northern Adriatic varies from <50 medium to large trawlers (250–800 hp) operating year-round, up to ca. 100 vessels when this activity becomes more profitable than otter trawl or pelagic fishing, such as following large recruitments to the exploitable scallop population. Average annual landings of *P. jacobaeus* in recent years are estimated to be around 1000 metric t (including shells) with a first-sale value of over US$ 2.5 million. Here we report on video observations of modern Rapido gear in action and investigate its impact on the large pinnacean mollusc, *Atrina fragilis*, and other members of the benthos.

Materials and methods

Study area

Fieldwork took place on 4–8 May 1995 aboard RV "Salvatore Lo Bianco" (30.2 m) in the Gulf of Venice. As a result of Holocene changes in sea level, relict residual sands characterize sediments of a wide area of the northern Adriatic (Colantoni *et al.*, 1979). With the exception of some outcrops of beachrocks and biogenic hard substrata, locally called "tegnue" and "trezze" (Newton and Stefanon, 1975), most of the area is trawlable, particularly along courses following the ancient coastal profiles. Extensive exploitable beds of scallops (*P. jacobaeus*, *A. opercularis*, and *A. glaber*) are present on these bottoms (Froglia, 1983; Šimunovic, 1997). A rather undisturbed area with high densities of *P. jacobaeus* was located using local knowledge of the region and underwater television (UWTV) sledge data (see below). The area covered ca. 10 km^2, centred at 45°13.5′N 12°47.1′E at a depth of 25 m (ca. 40 km SW of Venice, Fig. 1). The sea bed was level sand with scattered coralline rhodoliths.

Rapido trawl

Modern Rapido gear resembles a toothed beam trawl (Fig. 2a). It is lightly built and towed at 10–13 km h^{-1}, far faster than the 3–5 km h^{-1} that is typical for the heavier dredge designs that are used to catch scallops world-wide (Prado, 1987). Italian scallopers shoot one trawl per warp with 2–6 independent trawls towed at once (Fig. 2b). Fishing is continuous; while the catch from one trawl is retrieved and sorted, the other trawls

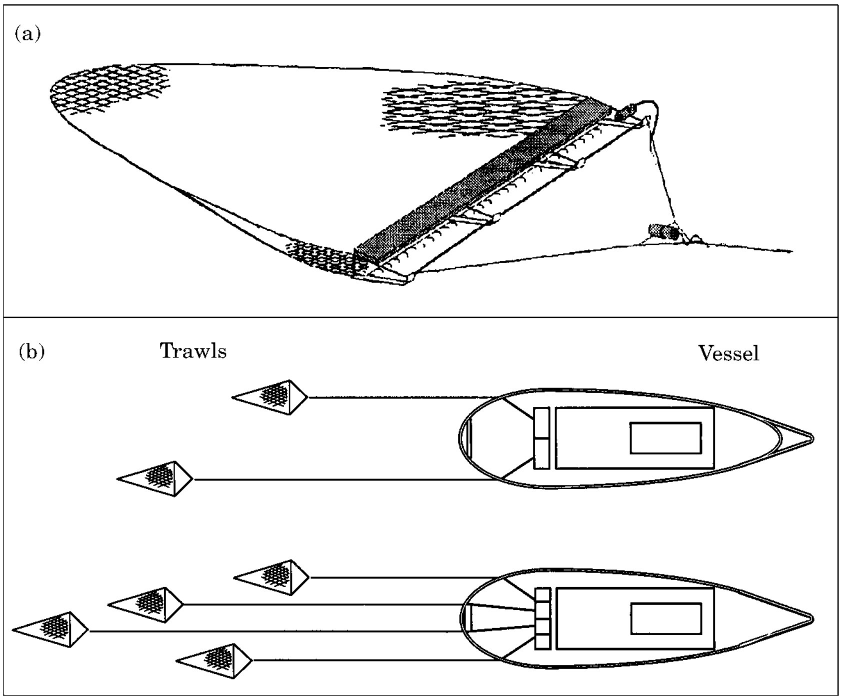

Figure 2. (a) Schematic diagram of a Rapido trawl with detail of frame and bridle camera mounting positions used in the present study, trawl width = 3 m. (b) Multiple trawls towed together to catch scallops and sole in the Adriatic (after Fiorentini and Cosimi, 1988).

remain on the sea bed. In our investigations, a single trawl was towed, so the effects reported here are less than that expected from commercial operations. The gear used was of typical commercial design; 3 m wide with four skids, each 12 cm wide. A wooden plank (300 × 30 × 2 cm) fitted to the front of the iron frame, at an angle of ca. 27° to the ground, acted as a spoiler to keep the trawl in contact with the seabed. There were 32 teeth along the trawl mouth, each was 4 mm wide and extended 2 cm below the skids. The teeth were fixed (cf. spring-loaded in UK scallop dredges) and were spaced 7.8 cm apart. A square 8 cm mesh nylon net bag was tied to the trawl frame to retain the catch. This extended 6.8 m behind the tooth bar. The belly of the net was protected by reinforced rubber diamond-mesh matting (stretched mesh size 24 × 15 cm). In air, the trawl weighed 170 kg in total and 120 kg without the net, chafer, and wooden spoiler.

Video surveys of the benthos before and after trawling

The scallop ground (Fig. 1) was sought using a low-light sensitive colour video camera (SIMRAD Osprey, Aberdeen, Model OE1362) mounted in conjunction with a compact underwater lamp (beam angle 70°; SIMRAD Osprey, Model OE1132) on a benthic sledge with 10 cm wide runners spaced 1 m apart, manufactured to specifications given by Shand and Preistley (unpubl.). A surface control unit (SIMRAD Osprey, Model OE1236) provided power and focus control for the UWTV and lighting units and was operated from the on-board laboratory. As the sledge was towed, a 1 m wide strip of seabed was viewed on a monitor and recorded on videotape (VHS; Ferguson Ltd, UK) with a time/date overlay provided by a video timer (VTG-88, FOR-A Co. Ltd, Japan). On each UWTV tow, the position of the vessel was recorded using a GPS receiver (Koden 900), vessel speed was measured by doppler log (Atlas Krupp Dolog 11D) and depth was recorded by echosounder (Elac LAZ A T23).

A preliminary survey of the scallop ground (Fig. 1) was made using towed UWTV to ensure that the area was clear of trawling obstructions and to record the distribution and abundance of undisturbed benthic organisms. Three 40 min UWTV tows were made at 2 km h^{-1} on 1 m wide transects running N–S, NE–SW, and NW–SE centred on a marked position at 45°13.5′N 12°47.1′E, giving an imaged area of 4000 m^2. Based on these surveys, an area of level sand with scallops was marked for experimental trawling. On 7 May 1995, two buoys were placed 60 m apart on an E–W bearing forming a "gate" half way along an experimental corridor. Pre-trawl densities of visible organisms were

Table 1. Paths of five 3 m wide Rapido trawls towed for 20 mins at 11 km h^{-1}, on *Pecten jacobaeus* grounds at 25 m depth in the Gulf of Venice, May 1995.

Tow	Date	Start time	Ship's position when dredge landed on seabed	Ship's heading
1	7 May 1995	10.29	45°07.8′N 12°40.2′E	E
2	7 May 1995	11.40	45°09.2′N 12°42.8′E	S
3	7 May 1995	14.55	45°12.1′N 12°44.6′E	NE
4	7 May 1995	16.42	45°13.2′N 12°47.8′E	NE
5	8 May 1995	14.35	45°15.5′N 12°47.3′E	SSW

recorded along this corridor by towing the UWTV between the buoys in a N–S direction at 2 km h^{-1} for 40 min. A Rapido trawl was then towed at 11 km h^{-1} on seven passes (each tow lasting 15–20 min) between the buoys on a N–S bearing to impact the marked strip of seabed. The UWTV sledge was then towed at 2 km h^{-1} for 40 min in a N–S direction between the buoys 1 h and 15 h after trawling to re-examine the surface appearance of the trawled area. The impact of the UWTV sledge runners on the benthos was minimal since the area in contact with the sediment was <1% of that of the Rapido trawl. For comparison with pre-trawl recordings, counts of visible organisms were obtained from those sections of the post-trawl video where the UWTV was seen to pass directly along the flattened Rapido trawl marks.

Video of Rapido trawl and catch analysis

The camera and lights from the UWTV sledge (above) were transferred on to a purpose-built adjustable bracket and mounted to view the action of the Rapido trawl at towing speeds of 5.5–15 km h^{-1}. The bracket was armoured to protect the camera, cable, and lights. The cable specification included Kevlar braid reinforcement and a 2.5 mm thick polyurethane sheath (Hydrocable Systems Ltd, Aberdeen) with sacrificial connectors which could be replaced rapidly in the event of damage caused by seabed obstructions. The camera was bolted to the bridle or the trawl frame and swivelled to view the action of the gear from various angles (Fig. 2a). The 3 m wide Rapido trawl was filmed along five 20 min tows at ca. 11 km h^{-1}, each fishing an estimated 11 000 m^2 of seabed. The timing and positions of these trawl runs are given in Table 1.

Upon hauling, the catches from these five trawls were emptied on deck and sorted into categories: inert debris, Algae, Porifera, Cnidaria, Polychaeta, Crustacea, *P. jacobaeus*, *A. opercularis*, Cephalopoda, other Mollusca, Echinodermata, Tunicata, and Pisces. Due to time constraints, each of these summated groupings were only drained and wet weighed intact on tows one to three. On all five tows, larger macrobenthic species (e.g. the cuttlefish *Sepia officinalis*) were identified, counted, and inspected for external signs of major mechanical damage (e.g. crushed bodies or cracked carapaces). Smaller macrobenthic species (e.g. the brittlestar *Ophiura albida*) were also identified and weighed, but were not enumerated due to time constraints. Samples of organisms that could not be readily identified were preserved in 5% borax-buffered formalin in sea water for subsequent laboratory examination.

Results

Video surveys before and after trawling

Analysis of film representing 4000 m^2 showed that the study area was uniformly sandy at 25 ± 1 m depth with ca. 2% cover of calcareous rhodoliths. The most abundant component of the large epibenthos was *A. opercularis* (mean density 2.82 m^{-2}) followed by ophiuroids, sponges, and the bivalve mollusc *Atrina fragilis* (Table 2). The shells of *A. fragilis* protruded up to 10 cm from the sand and provided a hard substratum for epilithic species like serpulids, hydroids, bryozoans, and juvenile pectinids. The mean abundance values in Table 2 are accurate for conspicuous organisms such as the holothurian *Holothuria forskali*, but underestimate the density of organisms that were difficult to discern, such as all juveniles and those *P. jacobaeus* which lay recessed and partially covered by sand. On average, only 2.3 100 m^{-2} *P. jacobaeus* were recorded using the UWTV sledge whereas 2.5–3.4 100 m^{-2} were caught on subsequent trawls of the area (see below). There were no obvious physical or ecological gradients detected across the area surveyed although the more numerous elements of the visible macrobenthos (e.g. pectinids) exhibited large-scale patchiness (with aggregations in the order of 500–1000 m^2).

Video images of the site marked for experimental trawling showed that it was typical of the area as a whole, being sandy and dominated by *A. opercularis* with more sparsely distributed *Ophiothrix* spp., sponges, tunicates, *Atrina fragilis*, *P. jacobaeus*, and *Holothuria forskali* (Table 3). Comparison of the pre-trawl

Table 2. Abundance of macrobenthic organisms observed before trawling using an underwater television (UWTV) sledge on three 40 min transects on a commercial scallop ground in the Gulf of Venice, 7 May 1995.

Taxa	Total counts	Mean abundance (number 100 m^{-2})
Aequipecten opercularis	11 280	282.00
Ophiothrix fragilis } *Ophiothirix quinquemaculata*	3281	82.03
Porifera	2807	70.12
Atrina fragilis	520	13.00
Holothuria forskali	125	3.13
Cerianthus membranaceus	109	2.71
Solitary tunicata	108	2.70
Pecten jacobaeus	92	2.30
Colonial tunicata	90	2.25
Inachus spp.	63	1.58
Unidentified Anthozoa	55	1.38
Astropecten irregularis	53	1.33
Naticid egg coils	46	1.15
Paguristes eremita } *Pagurus prideaux*	12	0.30
Osteichthyes	5	0.13
Archidoris pseudoargus	4	0.10
Echinus melo	4	0.10
Maja squinado	4	0.10
Aphrodita aculeata	3	0.08
Unidentified Holothuria	3	0.08
Solea kleini	2	0.05
Raja clavata	1	0.03
Corallinaceae	ca. 2% cover	ca. 2%cover
Filamentous Rhodophyta	<1% cover	<1%cover

Table 3. Minimum, mean, and maximum macrobenthos population densities on six 100 m^2 areas surveyed using a towed underwater television (UWTV) sledge immediately before and 15 h after Rapido trawling on a marked experimental area. Percentage differences are given for significant changes at the 95% probability level using the Mann-Whitney U-test.

Taxa	Pre-dredge min: mean: max (counts . 100 m^{-2})	Post-dredge min: mean: max (counts . 100 m^{-2})	% change in mean	p
Inachus spp.	0: 0.3: 1	1: 1.7: 3	+506%	<0.03
Paguridae	0: 0.2: 1	0: 0.8: 3	n.s.	n.s.
Osteichthyes	0: 0.2: 1	0: 0.6: 1	n.s.	n.s.
Ophiothrix fragilis } *O. quinquemaculata*	24: 35.5: 47	19: 37.3: 54	n.s.	n.s.
Aequipecten opercularis	415: 437.3: 479	398: 425.5: 472	n.s.	n.s.
Astropecten irregularis	0: 1.8: 3	0: 1.6: 4	n.s.	n.s.
Anthozoa	0: 0.2: 1	0: 0: 0	n.s.	n.s.
Porifera	25: 35.5: 43	19: 26.5: 39	− 25%	<0.05
Pecten jacobaeus	1: 3.3: 5	0: 1.0: 2	− 70%	<0.04
Holothuria forskali	1: 2.5: 4	0: 0.6: 2	− 73%	<0.03
Tunicata	1: 3.2: 6	0: 0.5: 2	− 84%	<0.02
Cerianthus membranaceus	0: 1.2: 2	0: 0.2: 1	− 85%	<0.05
Atrina fragilis	15: 19.8: 25	1: 2.6: 4	− 87%	<0.01
Naticid egg coils	2: 3.1: 5	0: 0.2: 1	− 95%	<0.01

population density estimates of the experimental plot (Table 3) with those obtained for the area overall (Table 2) reveals differences (e.g. Porifera and *A. opercularis*) that reflect the patchy distribution of the macrofauna. Emergent polychaete tubes (Maldanidae and Sabellidae) were common on the sediment surface in this area, but density estimates were not obtained because these taxa were difficult to resolve on the video image. The presence of a range of large infaunal organisms was also evident from surface features on the sand such as occasional mounds of fine sediment, probably created by burrowing thalassinidean shrimps, together with burrow openings of various morphologies and sizes. Video film taken 1 h after fishing revealed that sediment redistribution had been extensive, with suspended fine particles reducing horizontal through-water camera visibility from >20 m (pre-trawl) to near zero 1 m above the seabed. Disturbed sediment had settled 15 h after fishing, revealing distinctive tracks of the Rapido trawl as strips of flattened sediment. These strips lacked evidence of bioturbation or polychaete tubes and were littered with the smashed shells of Crustacea, infaunal bivalves and unidentified animal fragments. The 3 m wide trawl tracks were interspersed with strips of sediment that looked the same as that recorded prior to trawling, with no noticeable changes in the cover of polychaete tubes or bioturbation mounds.

The population densities of organisms recorded on six 100 m^2 areas of the trawl tracks 15 h after fishing (each equivalent to 3 min of film) were compared with their densities on six equivalent strips of the experimental area immediately prior to fishing in Table 3. For some species, the variance-to-mean ratios exceeded unity corroborating the operator's impression that they were patchily distributed within the marked experimental area either prior to, or after, disturbance. Thus the null hypothesis, that the recorded organisms had identical distributions prior to and after trawling, was tested using the non-parametric Mann-Whitney U-test. Despite the removal of individuals from the area as trawl by-catch, there was a significant increase ($p<0.03$) in the density of spider crabs, *Inachus* spp., which were seen clustered around exposed carrion on the trawl tracks. Although positive identifications were impossible, these were thought to have been mostly *I. dorsettensis* which outnumbered *I. communissimus* by 66:1 in Rapido catches from the area. Hermit crabs (*Paguristes eremita* and *Pagarus prideaux*) were also seen around the remnants of damaged animals after fishing, and both pagurids and fish were more abundant on the trawled tracks, although their increases were not significant at the 95% probability level. Some organisms, such as *A. opercularis* and *Ophiothrix* spp., were numerous before and after trawling with no significant changes found in their population densities. Many of these animals were small enough to pass through the trawl net and reductions in population density due to fishing were probably masked by individuals moving in from adjacent areas of unfished seabed. Significant decreases on the trawled track were noted in the population densities of the main target species (*P. jacobaeus*, $p<0.04$) together with >70% reductions in the abundances of several components of the associated macrobiota (Table 3). *Atrina fragilis* and large, naticid egg coils were particularly susceptible to removal exhibiting highly significant ($p<0.01$) decreases in abundance (87 and 95%, respectively).

Video of Rapido trawl

Video recordings revealed that the trawl skids, teeth, and rubber mesh belly remained in contact with the seabed at speeds <15 km h^{-1}. The teeth projected their full 2 cm into both sandy and muddy sediments and redistributed the surface layer creating a billowing cloud of suspended sediment in the wake of the gear. When towing speeds dropped below 3.5 km h^{-1} the towing warp and bridle periodically came into contact with the seabed, stirring up sediment ahead of the gear. The action of the depressor plank at high fishing speeds was shown when the camera was attached to the bridles in front of the trawl. When the depressor plank was removed from the upper face of the frame the gear fished inefficiently at speeds of 5.5–5.9 km h^{-1} due to poor penetration into the sediment; the whole trawl lifted off the seabed at 9–11 km h^{-1}.

Under normal towing conditions, the gear worked efficiently at the start of each tow, lifting *P. jacobaeus* from their recessed position on the sand and capturing them in the net (Fig. 3). Some swam as the gear approached but rarely gained enough height to escape the trawl mouth. Coralline rhodoliths and large shells became wedged in the trawl teeth and were either dragged through the surface of the sediment or were smashed before passing under, or into, the net. Trawl efficiency diminished with time as the forward-pointing teeth became clogged with debris. The teeth speared hard-shelled (e.g. the bivalve *Laevicardium oblongum*) and soft-bodied organisms alike (e.g. tunicates) and after 5 min of each tow the teeth were cloaked in the bodies of benthic organisms. When large objects became impaled on the teeth they caused the gear to lift, allowing some *P. jacobaeus* to pass underneath. The trawls caught 44% of the *P. jacobaeus* that were visible ahead of the gear on the five 20 min filmed tows. Although appreciable catches of *A. opercularis* were obtained, only 11% of the available population were caught; 80% passed under or through the trawls due to their small size and 9% escaped by swimming up into the water column. Video film taken with the camera pointing ahead of the trawl showed that some organisms (e.g. *Cerianthus membranaceus* and sabellid polychaetes) retracted into the sediment as the gear approached, while gadoids, and the ray, *Raja clavata*, swam above or to the side of the trawls, escaping unharmed. Some of the slower-moving organisms, such as the sea cucumber *Holothuria forskali*, were torn apart when hit by the trawl teeth. Disturbance to the benthos was

Figure 3. Rapido trawl with *Pecten jacobaeus* and an ophiuroid entering the trawl and debris clogging the trawl teeth.

concentrated on organisms living on or in the surface 2 cm of sediment, although bioturbation mounds up to 15 cm high were flattened, infaunal ventilation burrows were filled in, and shells of *Atrina fragilis* up to 25 cm long were speared on the trawl teeth and pulled from the sediment (Fig. 4).

Catch analysis

The Rapido gear showed high selectivity, with 78% of the biomass from five tows consisting of *A. opercularis* and *P. jacobaeus* (Fig. 5a). The mesh aperture (7–8 cm) allowed sediment and small organisms to pass through and very few of the *P. jacobaeus* caught were <7 cm in height (Fig. 6). Debris (e.g. man-made rubbish, dead shells, and rhodoliths) only formed 3% of the wet weight of the tows. Of the organisms attached to such debris, encrusting algae, serpulids, barnacles, and bryozoans were rarely damaged whilst erect algae, hydroids, sea anemones, and tunicates were often torn or squashed.

Catch data of the three weighed tows (one to three) are summarized in Table 4. Between 14.0 and 32.0 kg (1092–1728 individuals) *A. opercularis* and 1.5–21.0 kg (23–281 individuals) *P. jacobaeus* were caught on each 20 min tow. The by-catch composition also varied quantitatively between tows (as shown by large s.d., Table 4), but the total by-catch biomass was consistently low (Fig. 5a). For every kilogram of scallops caught (wet weight, including shells) an average of 0.2 kg of other organisms was retained. By weight, the non-pectinid catch comprised 51% tunicates, 23% echinoderms, 12% molluscs, 4% crustaceans, and 1–3% each for other phyla (Fig. 5b). A wide range of macro-organisms were retained in the trawls (78 taxa, Appendix), most of which were large, slow-moving animals that inhabited the sediment surface.

The most numerous by-catch species was the solitary tunicate *Pyura* sp., with a mean of 74 individuals caught per metre trawl width per hour of trawling (Fig. 7), followed by *Inachus dorsettensis*, the colonial tunicate *Botryllus schlosseri*, the sea urchin *Psammechinus microtubercularis*, and the starfish *Astropecten irregularis*. Infaunal organisms formed a low proportion of catches although the bivalves *Laevicardium oblongum* and *Atrina fragilis* were caught on every tow. Highly mobile organisms were also caught (e.g. swimming crabs, cephalopods, and fish), reflecting the high towing speed of the gear. Lethal damage to by-catch organisms varied depending upon their body form, size, and strength of protection, together with the period of time spent within the trawl before retrieval. Sea urchins, for example, were easily killed being epibenthic, slow-moving, and fragile. By-catch *Echinus melo* ranged from 7 to 13 cm in diameter and were particularly susceptible to damage (63% broken). In contrast, proportionally fewer (22% of the 123 caught) of the smaller (1.5–4.5 cm diameter) *Psammechinus microtubercularis* were broken since they had less chance of being hit by the trawl teeth, which were spaced ca. 8 cm apart. Organisms with thick protective shells were fatally damaged only in low proportions (e.g. none of the gastropods and only 10% of the hermit crabs), whereas 67% of the trawled fish and 90%

Figure 4. *Atrina fragilis* (25 cm long) caught on the teeth of a Rapido trawl after a 20 min tow.

of the thin-shelled *Atrina fragilis* sustained lethal damage (see Appendix).

Discussion

The UWTV surveys of scallop grounds in the Gulf of Venice provided information on the distribution of large epibiota. Filter-feeders characterized the community, as in other northern Adriatic regions (Fedra *et al.*, 1976), reflecting the high levels of primary production that occur in the nutrient-rich waters of the northern Adriatic basin (Fonda Umani *et al.*, 1992). Experimental trawling and UWTV surveys indicated that despite the relative homogeneity of the level sandy bottom, pectinids exhibited large-scale patchiness, as is typical for other scallop species (viz. *Chlamys varia*, Shafee, 1979; *Pecten maximus*, Thouzeau and LeHay, 1988; *Placopecten magellanicus*, Langton and Robinson, 1990). *Aequipecten opercularis* were particularly abundant with a mean population density of 2.8 m^{-2}. *Pecten jacobaeus* were less abundant with an estimated population density of 0.05–0.08 m^{-2} based on Rapido landings combined with filmed observations of gear efficiency at commercial towing speeds (average catch rate 44%).

Of the associated macrofauna, *Atrina fragilis* was of particular interest (mean population density 0.13 m^{-2}). *Atrina fragilis* and *Pinna nobilis* are the largest bivalves in Europe, reaching over 30 cm in length. Such Pinnacea are important "structural" species in sedimentary habitats (Warwick *et al.*, 1997) and their conservation importance is recognized in Mediterranean waters, with *P. nobilis* listed for protection in the EC Habitats Directive (1992). The emergent shells of *A. fragilis* provide a hard substratum for sessile species, thereby increasing habitat diversity in a predominantly sedimentary biotope. The presence of *A. fragilis* on Adriatic scallop grounds may be of particular importance to the fishery since juvenile pectinids were commonly attached to their shells. A parallel situation is reported in the Irish Sea (Service and Magorrian, 1997) where shells of the bivalve *Modiolus modiolus* are sensitive to demersal fishing disturbance but support sessile communities that allow *Aequipecten opercularis* spat to settle, enhancing recruitment to the surrounding sediment.

Information is lacking concerning movements of the Rapido trawl fleet, but in common with other fishing fleets its impact appears to be spatially and temporally heterogeneous (cf. Rijnsdorp *et al.*, 1998). Maurizio and Castagnolo (1986) showed that some areas of the Gulf of Venice scallop ground can be intensively exploited, recording an 83% drop in commercially sized *P. jacobaeus* in one area over a 6 month period of fishing. The abundance of *A. fragilis* suggests that our survey area had not been fished extensively in recent years since

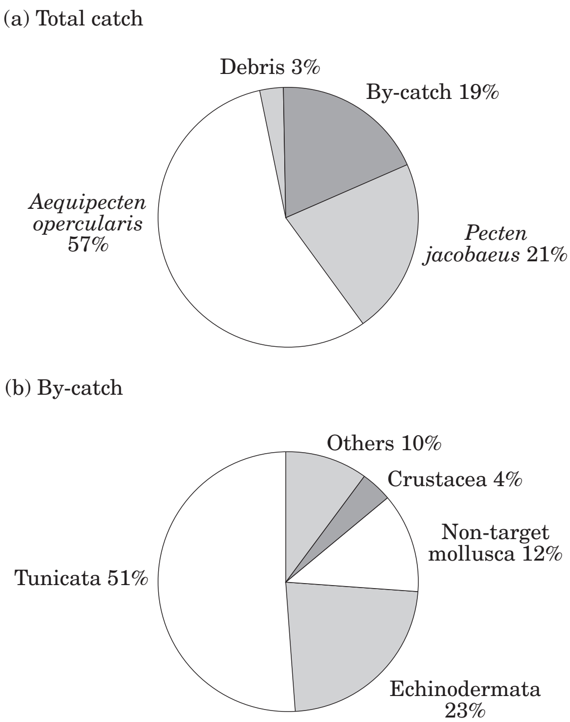

Figure 5. Relative composition of Rapido trawl catches from three 20 min (11 000 m^2) tows on the sandy scallop bed studied. Pie charts (a) and (b) illustrate the mean wet weights of components in the total catch and the by-catch, respectively.

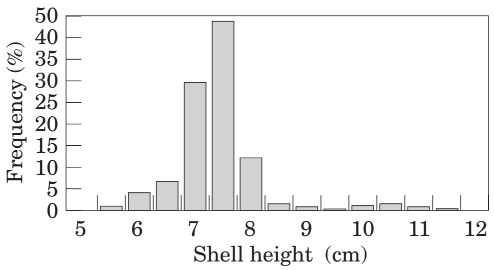

Figure 6. Size (shell height measured from the umbo to ventral margin) frequency distribution of *Pecten jacobaeus* (n=632) caught in four 20 min Rapido trawls towed at 11 km h^{-1} on sand at study site.

these bivalves are killed and/or removed by Rapido trawling.

The gross physical disturbance caused by Rapido fishing was similar to the overall sediment topographic smoothing noted for towed demersal gear on coarse sediments in many other areas (Thrush *et al.*, 1995; Hall-Spencer, 1995; Kaiser and Spencer, 1996; Schwinghamer *et al.*, 1996; Currie and Parry, 1996) and contrasts with the sediment roughening and persistent trenches that can be left on sheltered, muddy sites (Tuck *et al.*, 1998). Although redistribution and suspension of

Table 4. Mean wet-weight and standard deviation (± s.d.) of Rapido catch fractions trawled on three 20 min (11 000 m^2) tows on the study area. Tow positions (1, 2, and 3) given in Table 1.

Catch fraction	Mean wet-weights (g.100 m^{-2})	s.d.
Aequipecten opercularis	221.2	84.4
Pecten jacobaeus	79.6	96.8
Total scallops	300.9	171.4
Tunicata	35.1	32.7
Echinodermata	16.2	8.9
Other Mollusca	6.5	5.5
Crustacea	2.6	0.9
Porifera	1.9	1.1
Cnidaria	1.9	0.8
Cephalopoda	1.4	0.6
Pisces	1.3	1.7
Polychaeta	0.5	0.05
Algae	0.2	0.1
Total by-catch	67.7	32.3
Debris	10.0	4.2
Grand total	388.6	195.2

surface sediment was extensive, the sand had a low proportion of fine particles so settlement was rapid. Water clarity had returned to pre-trawling levels after 15 h. Trawl tracks lacked bioturbation mounds and burrow openings and many of the larger organisms had been broken or removed. The level sand condition of our study site contrasts with conditions on many scallop grounds where refugia are provided to benthic organisms by patches of hard ground that cause the gear to lose contact with the seabed and lower catch efficiency (Caddy, 1973; Hall- Spencer, 1995). Observations of the gear in action, catch analysis and video observations of an area of seabed before and after fishing showed extensive disturbance to the benthos. Given the mode and scale of the immediate impacts recorded here, there is the potential for Rapido trawling to have long-lasting effects on the benthos. Although the Rapido gear is much lighter than most scallop dredge designs (e.g. Newhaven dredges), the forces exerted upon objects hit at speed (and hence the degree of mechanical damage caused to organisms living on or near the sediment surface) may be similar to those exerted by heavier dredges since the diving vane improves penetration of the substratum. Rapido trawls catch more motile members of the biota (e.g. fish) and affected a larger area of seabed per unit time than typical scallop dredges which are towed more slowly. However, disturbance per unit area is less since the Rapido penetrates the seabed only shallowly (2 cm); typical scallop dredges penetrate to 10 cm and affect more of the infauna (Hill *et al.*, 1996; Kaiser *et al.*, 1996; Hall-Spencer, 1998). Filmed transects over Rapido tracks showed considerable reductions (>70%) in the population densities of

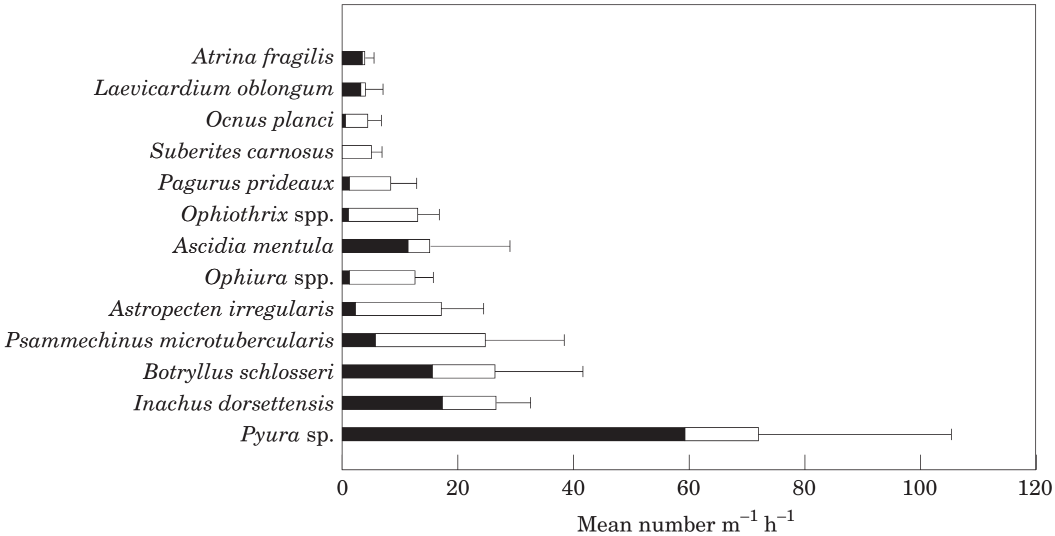

Figure 7. Mean numbers of the main by-catch macrofaunal species ($\geq$4 individuals caught per m trawl width her h trawl time) caught on five replicate Rapido trawls on study site. Shaded areas of bars indicate proportion with major visible damage. Error bars are +s.d. (n=5 except for Tunicata where n=4).

dominant members of the large, sessile biota such as *Cerianthus membranaceus* and *Atrina fragilis* which were mostly broken as they passed under the trawl teeth. MacDonald *et al.* (1996) devised a system of ranking benthic species in order of sensitivity to fishing activities. Using this scheme, *Atrina fragilis* ranks as "highly susceptible" to Rapido fishing due to its fragility, longevity, and size, whereas comparatively small gastropods, such as *Aporrhais pespelecani*, rank lower due to their ability to pass through the trawls and withstand mechanical impact.

Quantitative catch analyses revealed that the Rapido trawl was highly selective in its retention of benthic organisms. Most of the trawled material passed through with 78% of the catch weight comprising scallops. A broad spectrum of by-catch taxa were caught, several of which are routinely landed for human consumption (e.g. the spider crab *Maja squinado*, the gastropods *Aporrhais pespelecani* and *Bolinus brandaris*, the cephalopods *Eledone moschata*, *Octopus vulgaris*, and *Sepia officinalis*, as well as most fish). This is in contrast to practices in most northern European countries where by-catch is discarded at sea. High percentages of the large, fragile members of the epifauna and shallow-burrowing infauna were killed, although smaller, well-protected organisms (e.g. hermit crabs and gastropods) were not visibly damaged. These results correspond with those available for towed demersal gear from other areas (e.g. Caddy, 1973; Chapman *et al.*, 1977; Fonseca *et al.*, 1984; Eleftheriou and Robertson, 1992; Hill *et al.*, 1996). Records of fauna with severe mechanical damage (Fig. 6 and Appendix) provide minimum estimates of mortality since an unknown proportion would be expected to die subsequently due to internal injury, prolonged air exposure, enhanced susceptibility to predation, and/or lowered resistance to disease. Information regarding the fate of organisms discarded alive is scant for scallop fisheries (see Hill *et al.*, 1996; Ramsay and Kaiser, 1998) but certain members of the benthos would be expected to survive injuries inflicted by Rapido gear. Bivalve molluscs (e.g. *Ensis siliqua*, *Arctica islandica*, *Pecten maximus*) are often cracked on impact with trawled gear but can heal their shells to leave scars as a record of sublethal damage (Gaspar *et al.*, 1994; Witbaard and Klein, 1994; Hall-Spencer, pers. obs.). Starfish are also notable for their ability to survive contact with towed fishing gear (Kaiser and Spencer, 1995; Hill *et al.*, 1996) although in heavily fished areas >40% of starfish populations may have missing arms (Kaiser, 1996). How such high levels of damaged organisms affect the ecology of fished areas is not known.

The dead bodies and fragments of uncaught organisms that littered the tracks of the Rapido gear are a feature of bottom trawling that has been termed "non-catch mortality" (Bergman and Santbrink, 1994) which, together with a proportion of the discarded by-catch material, provides a potential source of food for benthic scavengers (Ramsay *et al.*, 1997). Scavenging animals observed in the present study included demersal fish and pagurids, with *Inachus* spp. exhibiting a highly significant increase in abundance along trawled tracks 15 h after the fishing impact. This aggregation of opportunistic species to feed on exposed, damaged, or killed fauna has also been reported in other scallop fisheries (e.g. Caddy, 1973; Chapman *et al.*, 1977; Thrush *et al.*, 1995; Currie and Parry, 1996).

Conclusions

Filming the direct action of Rapido scallop fishing, combined with quantitative analysis of by-catches and remote observations of the benthos before and after fishing provided detailed information on the direct effects of the gear. Short-term effects included reductions in the structural complexity of the habitat, liberation of space and the selective removal of a large proportion of the benthos. The indirect and longer-term effects are not known but are expected to favour opportunistic species and juvenile stages and a reduction in the abundance of large long-lived epifauna. Long-term changes of this nature have been detected in the marine ecosystem of the German Wadden Sea (Reisen and Reise, 1982; Reise, 1982), and several authors speculate that trawling is the cause of shifts in the community structure of the benthos (de Groot, 1984; Messieh *et al.*, 1991; Kaiser and Spencer, 1996; Philippart, 1998) and overlying plankton (Lindley *et al.*, 1995). Increasing food availability to motile predators and scavengers (through by-catch discards and non-catch mortality) may also contribute to shifts in the composition of benthic communities that are repeatedly disturbed by fishing, just as seabird populations benefit from discards at the sea surface (Garthe *et al.*, 1996). In the light of the observed short-term changes that result from the direct impact of Rapido trawling, it is proposed that the conservation of highly susceptible species (e.g. *Atrina fragilis*) would benefit from a scheme of selected closed areas where trawling is prohibited. This would provide refugia with mature scallops, which expend relatively little energy on somatic growth but are characterized by high fecundity (Shunway, 1991), thus enhancing the chances of recruitment to adjacent areas of commercial exploitation.

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Appendix. Mean number and standard deviation (s.d.) of organisms caught per metre trawl width per hour trawl line on replicate 20 min Rapido trawl runs (n=5, except for tunicata which were enumerated from 4 tows) on an Adriatic scallop bed at 25 m depth in May 1995. Percentages of those with severe mechanical damage are given. P=taxa that were present but not enumerated.

Taxa	Mean number $m^{-1} h^{-1}$	s.d.	% severely damaged
Porifera			
Cliona celata Grant	P	—	—
Hippospongia communis (Lamarck)	0.2	0.4	50
Myxilla sp.	1.5	1.3	50
Suberites domuncula (Olivi)	5.0	1.8	0
Sycon raphanus (Schmidt)	0.2	0.4	0
Tethya aurantium (Pallas)	0.2	0.4	100
Branching Porifera indet.	0.4	0.4	100
Encrusting Porifera indet.	P	—	—
Scyphozoa			
Aurelia aurita (L.)	0.2	0.4	100
Hydrozoa			
Nemertesia ramosa Lamouroux	1.5	1.0	67
Obelia sp.	P	—	—
Hydrozoa indet.	P	—	—
Anthozoa			
Adamsia carciniopados (Otto)	2.2	2.3	18
Calliactis parasitica (Couch)	3.6	2.3	0
Cerianthus membranaceus (Spallanzani)	0.2	0.4	100
Polychaeta			
Aphrodita aculeata (L.)	0.8	0.8	0
Chaetopterus variopedatus (Renier)	0.8	0.8	100
Owenia fusiformis Delle Chiaje	P	—	—
Decapoda			
Ethusa mascarone (Herbst)	1.8	1.3	0
Inachus dorsettensis (Pennant)	26.4	6.0	64
Inachus communissimus Rizza	0.4	0.9	50
Liocarcinus depurator (L.)	1.2	1.3	16
Macropodia rostrata (L.)	0.6	0.6	66
Macropodia tenuirostris (Leach)	0.4	0.5	50
Maja squinado (Herbst)	0.2	0.4	100
Paguristes eremita (L.)	1.4	1.5	14
Pagurus prideaux Leach	8.4	4.4	14
Pisidia longimana (Risso)	5.0	5.0	0
Gastropoda			
Aporrhais pespelecani L.	1.0	1.7	0
Bolinus brandaris (L.)	0.2	0.4	0
Calyptraea chinensis (L.)	P		0
Fusinus rostratus (Olivi)	0.2	0.4	0
Gibbula magus (L.)	0.6	1.34	0
Naticarius stercusmuscarum (Gmelin)	0.2	0.4	0
Ocenebra erinaceus (L.)	0.2	0.4	0
Opisthobranchia			
Archidoris pseudoargus (Rapp)	0.4	0.89	100
Scaphander lignarius (L.)	0.6	0.89	33
Pelecypoda			
Aequipecten opercularis (L.)	1302	289	3
Atrina fragilis (Pennant)	4.0	1.58	90
Callista chione (L.)	0.4	0.5	0
Chlamys glabra (L.)	0.2	0.4	0
Chlamys varia (L.)	1.6	1.5	0
Laevicardium oblongum (Gmelin)	4.0	3.0	80
Pecten jacobaeus (L.)	113	108	2
Timoclea ovata (Pennant)	0.2	0.4	0

Appendix *Continued*.

Taxa	Mean number $m^{-1}\ h^{-1}$	s.d.	% severely damaged
Cephalopoda			
Eledone moschata (Lamarck)	0.6	0.89	66
Loligo vulgaris Lamarck (egg clumps)	2.4	2.79	100
Octopus vulgaris Cuvier	0.2	0.4	0
Sepia officinalis (L.)	0.8	1.1	75
Bryozoa			
Sertella beaniana (King)	P	—	—
Erect Bryozoa indet.	P	—	—
Crustose Bryozoa indet.	P	—	—
Asteroidea			
Astropecten irregularis (Pennant)	17.0	7.2	12
Ophiuroidea			
Ophiothrix fragilis (Abildgaard) } *Ophiothrix quinquemaculata* (delle Chiaje) }	15.3	3.8	8
Ophiura albida Forbes } *Ophiura ophiura* (L.) }	12.5	3.1	8
Echinoidea			
Echinus melo Lamarck	1.6	1.14	63
Psammechinus microtuberculatus (Blainville)	24.6	13.6	22
Holothuroidea			
Holothuria forskali delle Chiaje	2.0	2.1	20
Ocnus planci (Brandt)	4.4	2.4	9
Tunicata			
Ascidia mentula O. F. Müller	15.0	13.8	75
Botryllus schlosseri (Pallas)	26.3	15.3	58
Ciona intestinalis (L.)	1.0	1.4	75
Didemnum sp.	P	—	—
Diplosoma sp.	P	—	—
Pyura sp.	71.8	33.1	82
Microcosmus ?sulcatus (Coquebert)	2.5	2.6	80
Phallusia mammillata (Cuvier)	2.5	1.3	70
Chondrichthyes			
Raja clavata L.	0.2	0.4	0
Blennius ocellaris L.	0.2	0.4	100
Gobius niger L.	0.2	0.4	100
Serranus hepatus (L.)	0.2	0.4	100
Solea kleini (Risso)	0.2	0.4	0
Trachinus draco L.	0.2	0.4	100
Algae			
Lithophyllum racemus (Lamarck) Foslie	P	—	—
4-siphoned *Polysiphonia* sp.	P	—	—
Encrusting Corallinaceae	P	—	—